UNITED STATES PATENT APPLICATION

OF

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FOR

THREE-STAGE OPTICAL AMPLIFIER HAVING FLAT SPECTRAL GAIN

BACKGROUND OF THE INVENTION

The present invention is directed toward optical amplifiers having a substantially flat spectral gain.

Wavelength division multiplexing (WDM) has been explored as an approach for increasing the capacity of existing fiber optic networks. In a WDM system, plural optical signal channels are carried over a single optical fiber with each channel being assigned a particular wavelength. Such systems typically include a plurality of receivers, each detecting a respective channel by effectively filtering out the remaining channels.

Optical channels in a WDM system are frequently transmitted over silica based optical fibers, which typically have relatively low loss at wavelengths within a range of 1525 nm to 1580 nm. WDM optical signal channels at wavelengths within this low loss "window" can be transmitted over distances of approximately 50 km without significant attenuation. For distances beyond 50 km, however, optical amplifiers are required to compensate for optical fiber loss.

Optical amplifiers have been developed which include an optical fiber doped with Erbium. The Erbium-doped fiber is "pumped" with light at a selected wavelength, e.g., 980 nm, to provide amplification or gain at wavelengths within the low loss window of the optical fiber. However, Erbium doped fiber amplifiers do not uniformly amplify light within the spectral region of 1525 to 1580 nm. For example, an optical channel at a wavelength of 1540 nm, for example, is typically amplified 4 dB more than an optical channel at a wavelength of 1555 nm.

While such a large variation in gain can be tolerated for a system with only one optical amplifier, it cannot be tolerated for a system with plural optical amplifiers or numerous, narrowly-spaced optical channels. In these environments, much of the pump power supplies

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energy for amplifying light at the high gain wavelengths rather than amplifying the low gain wavelengths. As a result, low gain wavelengths suffer excessive noise accumulation after propagating through several amplifiers.

Accordingly, optical amplifiers providing substantially uniform spectral gain have been developed. In particular, two stage optical amplifiers including an optical filter provided between first and second stages of Erbium doped fiber are known to provide gain flatness. In these amplifiers, the first stage is operated in a high gain mode and supplies a low noise figure to the second stage, while the second stage is operated in a high power mode. Although the second stage introduces more noise than the first, the overall noise output by the amplifier is low due to the low noise figure of the first stage. The optical filter selectively attenuates the high gain wavelengths, while passing the low gain wavelengths, so that the gain is substantially equal for each wavelength output from the second stage.

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~~Various improvements to such conventional amplifiers were patented by the assignee of the present invention. Particularly, U.S. Patents 5,057,959; 5,963,361; 6,049,413; and 6,061,171 disclose and claim various gain-flattened optical amplifiers. These disclosed amplifiers utilize two-stage amplification in which two stages of Erbium-doped fiber are pumped and in which an inter-stage variable optical attenuator is controlled. Various types of variable optical attenuator control are disclosed including adjusting the attenuation according to the gain of the first and second stages or the ASE (amplified stimulated emission) of the first and second stages.~~

Although these previously patented amplifiers provide excellent gain flatness and a low noise figure there is still room for improvement.

As noticed by the inventors, these two stage, gain-flattening amplifiers are typically designed to receive optical signals at a particular power level. Specifically, a flat gain response

may be achieved when the average population inversion of Erbium ions is at a particular level. This corresponds to a fixed input power level (for a particular set of pump power levels). When the input power level varies from this optimal input power level, the gain flatness suffers.

In other words, when the total power level of all optical signals input to the amplifier differs from the desired input level, the amplifier can no longer amplify each wavelength with substantially the same amount of gain. Accordingly, the conventional gain-flattened amplifiers discussed above are unable to receive input optical signals over a wide range of power levels while maintaining substantially uniform gain at each wavelength.

SUMMARY OF THE INVENTION

Consistent with an embodiment of the present invention, an optical amplification device is provided, including a first segment of active optical fiber having a first end portion coupled to an optical communication path carrying a plurality of optical signals, each at a respective one of a plurality of wavelengths, and a second end portion. The first segment of active optical fiber receives the plurality of optical signals through the first end portion and outputs the plurality of optical signals through said second end portion.

Furthermore, a dispersion compensating element is coupled to the second end portion of the first segment of active optical fiber.

In addition, the optical amplification device further includes a second segment of active optical fiber having a first end portion coupled to the output of the dispersion compensating element. The plurality of dispersion compensated optical signals are supplied to the first end portion of the second segment of active optical fiber via the output port of the dispersion

compensating element. The plurality of optical signals are next output from the second segment of active optical fiber via the second end portion of the second segment of active optical fiber.

A variable optical attenuator is also provided having an input port receiving the plurality of optical signals coupled to the second end portion of the second segment of active optical fiber. The variable optical attenuator further includes a control port that receives an attenuation control signal, and an output port.

In addition, the optical amplification device includes a third segment of active optical fiber having a first end portion coupled to the output port of the variable optical attenuator and a second end portion. The plurality of dispersion compensated optical signals propagate through the variable optical attenuator and are supplied to the first end portion of the third segment of active optical fiber via the output port of the variable optical attenuator. The plurality of optical signals are next output from the third segment of active optical fiber via the second end portion of the third segment of active optical fiber.

A control circuit is further provided which is optically coupled to the optical communication path. The control circuit senses variations in the input power applied to the amplification device and the power loss across the variable optical attenuator and outputs the attenuation control signal in response to the sensed input power and loss across the variable optical attenuator. The optical attenuator, in turn, attenuates the plurality of optical signals in response to the attenuation control signal in order to
achieve a flattened gain profile.

In accordance with an additional embodiment of the present invention, the attenuation of the optical attenuator is controlled in accordance with the span loss error indicative of a change in the loss associated with a previous span to which the amplification device is connected and in

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accordance with a dispersion compensating element loss error indicative of a change in the expected loss across the dispersion compensating element.

In a further embodiment of the present invention, the attenuation of the optical attenuator is controlled in accordance with an additional factor. The additional factor is an offset value that accounts for any residual non-flatness in the amplification device.

Moreover, in accordance with an additional embodiment of the present invention, received power of each of a plurality of WDM signals is measured after propagation through a chain of amplifiers, each of which includes one of the three stage amplifier embodiments of the invention which include a dispersion compensating element between the first and second stages and a variable optical attenuator coupled between the second and third stages. Based on the received power, the attenuation of the optical attenuator in each amplifier is adjusted so that the received power associated with each WDM signal is substantially the same.

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BRIEF DESCRIPTION OF THE DRAWINGS

Advantages of the present invention will be apparent from the following detailed description of the presently preferred embodiments thereof, which description should be considered in conjunction with the accompanying drawings in which:

Fig. 1 illustrates an optical amplifier in accordance with a first embodiment of the present invention;

Fig. 2 illustrates an optical amplifier in accordance with a second embodiment of the present invention;

Fig. 3 illustrates an optical amplifier in accordance with a third embodiment of the present invention;

Fig. 4 illustrates an optical amplifier in accordance with a fourth embodiment of the present invention;

Fig. 5 illustrates an optical amplifier in accordance with a fifth embodiment of the present invention;

Fig. 6 illustrates an optical amplifier in accordance with a sixth embodiment of the present invention;

Fig. 7 illustrates an optical amplifier in accordance with a seventh embodiment of the present invention;

Fig. 8 illustrates a service channel add/drop configuration in accordance with an aspect of the present invention;

Fig. 9 illustrates an additional service channel add/drop configuration in accordance with an aspect of the present invention; and

Fig. 10 illustrates a block level diagram of an optical communication system in accordance with the present invention.

DETAILED DESCRIPTION

Turning to the drawings in which like reference characters indicate the same or similar elements in each of the several views, Fig. 1 illustrates an optical amplifier 1 in accordance with a first embodiment of the present invention. Optical amplifier 1 generally includes the components between input port 12 and output port 42.

Optical amplifier 1 is a three stage amplifier including a first amplifier stage 20, second amplifier stage 30 and third amplifier stage 40.

Each of the stages 20, 30, 40 of optical amplifier 1 includes a section of active optical fiber that is typically doped with a fluorescent material, such as Erbium, and pumped with light at a wavelength different than the amplified optical signals, e.g., 980 nm and/or 1480nm as is known in the art. Pump lasers are coupled to the active optical fiber in each stage 20, 30, 40 excite the fluorescent material. The pump light is of sufficient magnitude and the composition of active optical fiber is such that the optical signals output from each stage are amplified.

Preferably and as shown in Fig. 1, the first stage amp 20 and second stage amp 30 are each pumped by a high power 980nm pump (22 and 32, respectively) and the third stage is pumped by two high power 1480nm pumps 42, 44. Pump 42 operates in a copropagating mode and pump 44 operates in a counterpropagating mode.

Although a variety of pump configurations may be utilized and Fig. 1 only shows one such configuration, it is preferred that the first and second stage amps 20, 30 are highly inverted and provide high gain and low noise figure with respect to the third stage amp 40. The output stage (third stage amp 40) is a power amplifier with the 1480nm pumps providing high optical conversion efficiency with respect to the first and second stage amps 20, 30.

As further shown in Fig, 1, a filter 150 and variable optical attenuator 60 are preferably located between the second amp stage 30 and the third amp stage 40 so that the effect on the noise figure and output power of the amplifier 5 is minimized. Filter 150 may be a gain flattening filter or used to drop/add service channels (see Figs. 6-9 and accompanying description below)

Figure 1 shows a preferred pump arrangement and configuration of the three stage amp 1 relative to the filter 150 and variable optical attenuator 60.

Figure 2 further illustrates a control arrangement for the optical amplifier 5 and assumes that a pumping arrangement such as the one shown in Figure 1 would be utilized to pump the three stages 20, 30, 40 of the amplifier 5. Optical amplifier 5 generally includes the components between input port 12 and output port 42.

As shown in Figure 2, the input port 12 of optical amplifier 5 is connected to a span 10 the loss of which may vary. The symbol used to represent span 10 is similar to the one used to represent a variable optical attenuator and is intended to indicate the possibility that the loss of span 10 may vary. As mentioned above, a variation in span 10 loss will typically change the signal power input to amplifier 5 which would negatively affect the gain flatness unless corrective action were taken such as the actions taken by the invention as further described below.

In order to measure the input power variation, the amplifier 5 includes a known coupler 15 connected to input port 12 that receives a plurality of optical signals, each at a respective one of wavelengths λ_1 to λ_n typically within a range of 1500 to 1590 nm. The plurality of optical signals may constitute WDM (wavelength division multiplexed) signals.

Coupler 15, like couplers 25 and 27, may be constructed with a conventional optical tap or splitter, which supplies each of the plurality of optical signals to both the input 20-1 of the first amp stage 20 and to O/E (optical-to-electrical converter) 82. The power of optical signals supplied to input 20-1 of the first amp stage 20 is typically significantly more than the power of optical signals supplied to the O/E 82. For example, the power supplied to O/E 82 may be approximately 2% of the power fed to input 20-1 (neglecting coupler loss, for simplicity).

The optical signals output from coupler 15 are supplied to a first amp stage 20, which provides a first stage of amplification.

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After the first stage of amplification, the optical signals are next supplied to coupler 25. Coupler 25 may constructed with a conventional tap or splitter in the same fashion as coupler 25. Coupler 25 supplies a small portion of the light to O/E 84 with the majority being sent to dispersion compensating element 50. The output of dispersion compensating element 50 is fed to yet another coupler 27 which, in turn, feed a small portion to O/E 86 and the majority to the input 30-1 of the second stage amp 30.

In other words, couplers 25 and 27 respectively tap the input and output of dispersion compensating element 50 so that a dispersion power loss value may be measured as further described below.

Ignoring the couplers 25 and 27 for a moment, the dispersion compensating element 50 is provided between output port 20-2 of the first amp stage 20 and the input port 30-1 of the second amp stage 30. Dispersion compensating element 50 provides dispersion compensation for the optical signals output from the first amp stage 20, and can include a variety of elements such as a segment of known dispersion compensating fiber (DCF) or a dispersion compensating Bragg grating or both. It is noted that dispersion compensating element 50 may also be provided at any appropriate location within any one of the embodiments of the present invention.

Following dispersion compensating element 50 and coupler 27, the optical signals are next supplied to input port 30-1 of the second stage amplifier 30 which provides a second stage of amplification. The second stage amp 30 may be pumped as shown in Figure 1 or with another pumping arrangement keeping in mind that the second stage amp 30 is preferably pumped such that the Erbium ions are highly inverted and to provide high gain and low noise figure to a signal passing therethrough.

The output of the second stage amp 30 is provided to a variable optical attenuator 60. Variable optical attenuator 60 has an attenuation which can be variably controlled in accordance with an attenuation control signal supplied to control port 60-1. Variable optical attenuator 60 may be constructed from known devices such as the commercially available variable optical attenuators from JDS Fitel and E-Tek, for example, that attenuate each of the optical signals by substantially the same amount, and as discussed in greater detail, controllably attenuates the optical signals so that amplifier 5 provides substantially flat gain profile for the optical signals.

The output of variable optical attenuator 60 is then supplied to the third stage amp 40 and then to the output port 42 of the optical amplifier 5. As mentioned above, the output stage (third stage amp 40) is preferably a power amplifier pumped so as to provide high optical conversion efficiency.

As further shown in Fig. 2, optical signals output from couplers 15, 25, and 27 are supplied to a control circuit 80 including conventional O/E converters 82, 84, and 86 (e.g. photodetectors), which respectively convert the optical signals to electrical signals. The electrical signals are respectively supplied to an attenuator adjustment circuit 70 which includes known analog-to-digital (A/D) converter circuits 92, 94 and 96 which convert the received electrical signals, typically in analog form, to digital signals.

The attenuator adjustment circuit 70 also includes controller 100, memory device 110 and digital-to-analog (D/A) converter 115. Other circuitry may be provided between photodetectors 82, 84, 86 and controller 100, as necessary, for example, interface circuits and voltage level adjustment circuits. Moreover, the A/D converters 92, 94, 96 may be eliminated entirely if the controller 100 and memory device are implemented with analog components.

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Although controller 100 of Figure 2 could be implemented as an analog device, the second embodiment shown in Fig. 2 is preferably implemented with a digital controller 100. Specifically, controller 100 may be implemented with a conventional microprocessor, central processing unit (CPU) or application specific integrated circuit (ASIC), which receives the electrical signals output from A/D converters 92, 94, and 96 and calculates an appropriate attenuator adjustment value that improves the amplifier 5 gain flatness in response thereto. Controller 100 further outputs an attenuation control signal in accordance with the attenuator adjustment value so that amplifier 5 maintains a substantially flat gain profile.

Controller 100 preferably calculates the attenuator adjustment value according to the input power level and the dispersion compensating element power loss. The coupler 15 and O/E 82 provide a mechanism that measures the amount of input power to amplifier 5. Likewise, couplers 25, 27 and their associated O/E converters 84, 86 provide a mechanism that measures the loss across the dispersion compensating element 50. Controller 100 may find the sum of the input power level value and the dispersion compensating element power loss value to determine the attenuator adjustment value.

The attenuator adjustment value is supplied by controller 100 to digital-to-analog converter circuit 115, which, in turn, feeds an attenuation control signal to control port 60-1 of variable optical attenuator 60, to appropriately adjust the attenuation thereof. Other circuitry may be provided between controller 100 and attenuator 108, as necessary, e.g, for voltage level adjustment, etc.

Thus, variations in input power applied to the first stage amp 20 as well as the loss across dispersion compensating element 50 can be offset by corresponding changes in the attenuation of variable optical attenuator 50 so that optical amplifier 5 maintains a substantially flat gain profile.

The memory device 110 may aid in the calculations performed by controller 100. For example, the dispersion compensating element loss value may not change very much over time. In that case, the mechanism for measuring the dispersion compensating element loss (couplers 25, 27; O/E 84, 86; and A/D 94, 96) may measure this loss value upon installation of the dispersion compensating element 50 and the controller 100 may store this loss value in memory device 110 for future reference. Preferably, however, this loss value is measured at least on a periodic basis.

Fig. 3 illustrates optical amplifier 6 in accordance with an alternative embodiment of the present invention. Optical amplifier 6 is similar to optical amplifier 5 but attenuator adjustment circuit 70 further includes a comparator circuit 105. Comparator circuit 105 is connected to the A/D converters 94, 96 as shown in Figure 3 and compares the input power to the output power of dispersion compensating element 50. In other words, comparator 105 determines the dispersion compensating element loss value and supplies this value to controller 106.

Controller 106 of Fig. 3 is similar to controller 100 of Fig 2 but need not perform the calculation of the dispersion compensating element loss value. Instead, controller 106 inputs this loss value directly from comparator 105 and thereby simplifies the calculation of the attenuator adjustment value. In this way, a simpler device may be utilized to construct controller 106 as compared with controller 100. Comparator 105 may be constructed from a variety of devices such as a conventional subtractor. Once found, the dispersion compensating element loss value may be stored in memory device 115 for future reference as in the first embodiment.

Furthermore, the calculations performed by controllers 100 and 106 may be based on error values instead of absolute measurement values. More specifically, controllers 100 and 106 may calculate a span loss error value which is the difference between the expected (or previously

determined) span loss value and the current span loss value 10. Likewise, controllers 100 and 106 may calculate a dispersion compensating element loss error value which is the difference between the expected (or previously determined) DCE 50 loss value and the current DCE 50 loss value. The expected (or previously determined) reference values may be stored in memory device 110 to enable such calculations.

Fig. 4 illustrates optical amplifier 7 in accordance with another alternative embodiment of the present invention. Optical amplifier 7 is similar to optical amplifier 5 but attenuator adjustment circuit 70 includes alternative components. Namely, the attenuator adjustment circuit 70 includes a span loss error calculator connected to A/D 92 and to a reference span loss 125. Attenuator adjustment circuit 70 also includes a DCE loss error calculator connected to A/D 94, A/D 96 and to a reference DCE loss 135.

The reference span loss 125 and reference DCE loss 135 may be constructed with, for example, a memory device, a register, or a voltage reference. In some applications, the reference losses 125, 135 are known values that can be built into the optical amplifier by programming memory device(s) or registers with these values or with predetermined electrical signal sources (e.g. voltage references). The actual and reference loss values are respectively input to the span loss error calculator 120 and DCE loss error calculator 135 which output the span loss error and DCE loss error to controller 107 which utilizes the loss errors to calculate the attenuator adjustment value.

Fig. 4 also illustrates another alternative of the invention: an offset 145 may be used to improve the calculation of the attenuator adjustment value. Offset 145 may be constructed with, for example, a memory device, a register, or a voltage reference. The offset 145 may be utilized to compensate for the inherent or residual non-flatness of the amplifier 7. Specifically, many

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amplifiers of the invention (1,5,6,7,8,9,9') have a residual or inherent non-flatness depending upon a number of factors such as the variation in the length of Erbium-doped fiber in each of the amp stages 20, 30, 40; variation in gain-flattening filters (discussed below); and variations in other optical components.

During an optional but preferred calibration process, the optical amplifier 7 (or any of the optical amplifiers 5, 6, 8, or 9 disclosed herein) is fed with a comb of input signals spanning the expected range of wavelengths to be amplified (or with a white light source). The optical attenuator 60 is adjusted (either manually or automatically by controller 107) until the non-flatness of the output spectrum is at a minimum. This adjusted value is deemed an attenuator offset level and may be stored in memory device 110 or in offset 145 as, for example, a voltage reference.

If the offset is used, then controller 107 calculates the attenuator offset value as a function of the span loss error, DCE loss error, and the attenuator offset value. For example, the attenuator offset value may be the sum of the span loss error, DCE loss error and the attenuator offset value.

As indicated by the broken lines of the A/D and D/A converters 92, 94, 96 and 115; the embodiment of Fig. 4 is particularly well-suited to implementation with analog circuitry. For the example, an analog subtractor can be used to implement span loss error calculator 120 and the DCE loss error calculator 130 and a voltage reference can be used to implement reference span loss 125 and reference DCE loss 135. The controller 107 may be a simple summing circuit the analog output of which could be directly applied to the variable optical attenuator 60. Of course, voltage level correction may be utilized to correct the analog voltage level applied by controller 107 to the variable optical attenuator 60.

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Fig. 5 illustrates optical amplifier 8 in accordance with another alternative embodiment of the present invention. Optical amplifier 8 of Fig. 5 is similar to optical amplifier 7 of Fig. 4 but attenuator adjustment circuit 70 includes alternative components. Namely, the attenuator adjustment circuit 70 includes a look-up table 180 and controller 108 may be simplified with respect to controller 107 of Fig. 4.

More specifically, the attenuator adjustment circuit 70 of Fig. 5 may utilize a look-up table 180 that which stores loss error values, as represented by the digital signal, and corresponding attenuator adjustment values. Accordingly, in response to the output from controller 108, look-up table 180 outputs an associated attenuator adjustment value corresponding to a substantially flat amplifier gain spectrum. Controller 108 need only sum the span loss error value, DCE loss error value and offset and apply the sum to the look-up table 180 in order to find the corresponding attenuator adjustment value.

Fig. 6 illustrates optical amplifier 9 in accordance with another alternative embodiment of the present invention. Optical amplifier 9 of Fig. 5 is similar to optical amplifier 5 of Fig. 1 but adds filter 150 between the second stage amp 30 and the third stage amp 40. An optical isolator (not shown) may also be used between the filter 150 and the second stage amp 30 to improve performance. Filter 150 may be constructed from a commercially available filter(s) (e.g. from JDS Fitel).

Filter 150 may selectively attenuate certain optical signal wavelengths, e.g., the high gain wavelengths output from second stage amp 30, while permitting other wavelengths to pass substantially unattenuated. In this way, the filter 150 may perform gain flattening.

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Fig. 8 shows an alternative way of using filter 150 other than the gain flattening purpose discussed above. Specifically, filter 150 may be used to inject and remove a service or monitoring channel signal. Such service or monitoring channel signals typically have a wavelength lying outside the range of operating wavelengths (e.g., 1500 nm - 1590 nm) of optical signals applied to input port 12. These service channel wavelength(s) can be inserted and extracted from amplifiers 1,5,6,7,8,9 or 9', as discussed, for example, in U.S. Patent No. 5,532,864, incorporated by reference herein.

As further shown in Fig. 8, filter 150 may reflect the received service channel signals, typically having a wavelength of 1625-1650 nm, to service channel (SC) receiver 200, and directs the service channel signal emitted by service channel (SC) transmitter 210 to input port 60-2 of attenuator 60. The service channel add/drop configuration shown in Fig. 8 can also be incorporated into any of the amplifiers 1, 5, 6, 7, or 8 shown in Figs. 1, 2, 3, 4, and 5.

It is noted that filter 150 can serve both purposes of adding/dropping the service channel, as well as selectively attenuating the high gain wavelength i.e., for gain flattening. Alternatively, separate filters 150 can be provided for service channel add/drop and gain flattening, respectively.

Fig. 7 illustrates amplifier 9' in accordance with a further embodiment of the present invention. Amplifier 9' is similar to amplifier 9 discussed above in relation to Fig. 6, but includes an additional filter 155. In this embodiment, filter 150 typically attenuates one group of wavelengths, while filter 155 attenuates another group in order to provide gain flattening.

Alternatively, as further shown in Fig. 9, filter 150 can be used to direct first service channel signals to service channel receiver 300, while filter 155 can be used to couple second service channel signals emitted by service channel transmitter 320 to the third amp stage 40 for

output from amplifier 9'. Additional filter(s) can also be provided in Fig. 9 to provide spectral filtering of the high gain wavelengths to obtain flattened gain in the manner discussed above. Alternatively, filters 150 and 155 can be provided which both selectively attenuate the high gain wavelengths and perform the service channel add or drop.

The embodiment shown in Fig. 9 may be advantageous in having reduced cross-talk between the added and dropped service channel signals compared to the add/drop configuration shown in Fig. 8. In particular, the add/drop configuration shown in Fig. 8 includes a single filter 150 for both adding and dropping the service channel signals. Typically, filter 150, however, is not entirely reflective at the service channel wavelength. Accordingly, a portion of the second service channel signals emitted by service channel transmitter 210 in Fig. 8 can pass through filter 150 to service channel receiver 200, thereby resulting in cross-talk or interference between the received service channel signal and the portion of the service channel signal emitted by service channel transmitter 210.

In Fig. 9, the service channel signals are dropped and added with separate filters 150, 155. Accordingly, any portion of the service channel signals emitted by service channel transmitter 320 that propagates toward attenuator 60, and not to second stage amp 30, as intended, are significantly attenuated by attenuator 60, thereby effectively eliminating any cross-talk at receiver 300. The add/drop configuration shown in Fig. 9 may be incorporated into all the amplifiers discussed above.

Fig. 10 illustrates an alternative embodiment of the present invention in which the attenuators included in a chain of amplifiers are adjusted substantially simultaneously so that the power associated with each optical signal output from the chain is substantially the same.

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In particular, Fig. 10 illustrates a WDM system 500 including a plurality of transmitters Tr_1 to Tr_n (400-1 to 400-n) each of which emits one of a plurality of optical signals. Each of the plurality of optical signals are at a respective one of a plurality of wavelengths. The optical signals are output to and combined, using a conventional WDM multiplexer 410, onto an optical communication path 410, comprising, for example, an optical fiber. A chain of optical amplifiers 420-1 to 420-5 are coupled in series along optical communication path 410. Each of the optical amplifiers (420-1 to 420-5) may have a structure similar to that of any one of optical amplifiers (1,5,6,7,8,9, or 9') discussed above, including an optical attenuator 60 coupled between second and third stage amps 30, 40.

A WDM demultiplexer 440 is coupled to optical communication path 410 at the end of the amplifier chain. Each of the outputs of WDM demultiplexer 410 are coupled to a respective one of receivers 450-1 to 450-n, which convert the optical signals to corresponding electrical signals. Received power modules 460-1 to 460-n sense these electrical signals and determine the received optical power and/or signal to noise ratio associated with each optical signal. The received power modules 460-1 to 460-n supply power level signals corresponding to the received optical powers to monitor circuit 470, which determines whether the received power levels are substantially equal. If not, monitor circuit 470 outputs an adjustment signal to tilt control circuits 430-1 to 430-5.

In response to the adjustment signal, each of tilt control circuits 430-1 to 430-5 outputs a corresponding attenuation control signal to the attenuators in amplifiers 420-1 to 420-5, thereby adjusting the output powers of the optical signals supplied from each of these amplifiers. Received power modules, in turn, detect the new optical power levels and supply new power level signals to monitor circuit 470. Monitor circuit 470 typically continues to output adjustment

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signals to tilt control circuits 430-1 to 430-5, thereby maintaining substantially equal power levels for each optical signal.

While the foregoing invention has been described in terms of the embodiments discussed above, numerous variations are possible. Accordingly, modifications and changes such as those suggested above, but not limited thereto, are considered to be within the scope of the following claims.

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